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A STUDY OF TEMPORAL AND RADIAL DEPENDENCIES OF THE ANOMALOUS HELIUM AND OXYGEN NUCLEI

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ABSTRACT

The intensity of the low energy anomalous Helium and Oxygen components has been continuously monitored by telescopes on the Pioneer 10 and IMP 7 and 8 spacecraft since 1972. After a period of relatively small temporal changes at earth between 1972 and 1978, during which it was possible to study the radial gradients of these components out to ∿ 15 AU, large temporal changes were observed in 1978-1980 associated with the onset of the new solar modulation cycle. During this time period the anomalous He and O intensities at Pioneer 10 have decreased by a factor > 10, however, both anomalous components were still present in the summer of 1980 at ∿ 20 AU. At the earth similar large intensity changes have occurred. At Pioneer 10 the relative modulation of He nuclei is ∿ 1.4x that of O nuclei at the same energy/nuc during this time period.

1. Introduction

The origin of the anomalous components of low energy cosmic rays, of which He and O are the most obvious examples, presents many intriguing questions. These components "appeared" at earth for the first time in 1972 during a time of low solar modulation. They remained at essentially the same intensity level until early 1978 when solar modulation effects related to the onset of the new solar cycle produced a drastic decrease in their intensity. The possibility that these components are singly charged as opposed to the fully stripped ordinary cosmic ray nuclei has important implications for the solar modulation effects on them and also on their interplanetary radial gradient. Indeed, an understanding of these aspects of the behavior of the anomalous charges may improve our understanding of solar modulation in general; a problem, that after a quarter century of study, still defies a completely satisfactory solution.

We have examined the temporal variations and the interplanetary radial gradient of these components using data from the GSFC-UNH experiment on Pioneer 10 and 11 and the GSFC and Caltech experiments on IMP-7 and 8. This paper updates our earlier reports (Webber et.al., 1975, 1977, and 1979), to late 1980 when Pioneer 10 was ∿ 23 AU from the sun and solar modulation effects from the new cycle were well established.

2. The Data.

In Figure 1a is shown the intensity of 9.5-23.5 MeV/nuc O nuclei in 3 month intervals from the time of Pioneer 10 launch. In Figure 1b the 10-21.6 MeV/nuc He nuclei intensity is shown in 26-day intervals. Up to early 1978 the progressive separation of intensities at earth and at Pioneer 10 is evidence of an interplanetary radial gradient. After this, temporal changes were dominant and although Pioneer 10 continued outward from 15 to 23 AU, the He intensity is observed to decrease by a factor $\sim$ 12 and the O intensity by $\sim$ 8 by late 1980. Comparable decreases were observed at earth although because of the low intensities it is difficult to extract accurate intensity values in 1980.

It is useful to compare the intensities observed on Pioneer 10 and those at earth during this time period. The ratio P-10/earth, for both He and O nuclei is shown in Figure 2. This ratio is a direct measure of the radial gradient and in the period up to early 1978 temporal variations play a minor role. It is seen that both components have an average radial gradient $\sim$ 15%/AU out to $\sim$ 15 AU. After the large decreases in intensity in 1978, no large changes in the average gradients of the two components are observed.

An examination of the energy spectra reveals the energy dependence of the changes occurring after 1978. In Figure 3 the He spectra at Pioneer 10 and at earth for four time periods in 1978-1980 are shown. It is evident that the intensity changes at both locations are much larger at lower energies but evidence for the anomalous He component still remains at Pioneer 10 in 1980. At earth clear evidence for this component disappears in 1979. In Figure 4 the spectra of O nuclei are shown for two time periods, before and after the large intensity decrease. Anomalous O is still present at Pioneer 10 in 1979 and probably at earth as well although the intensity level is very low.

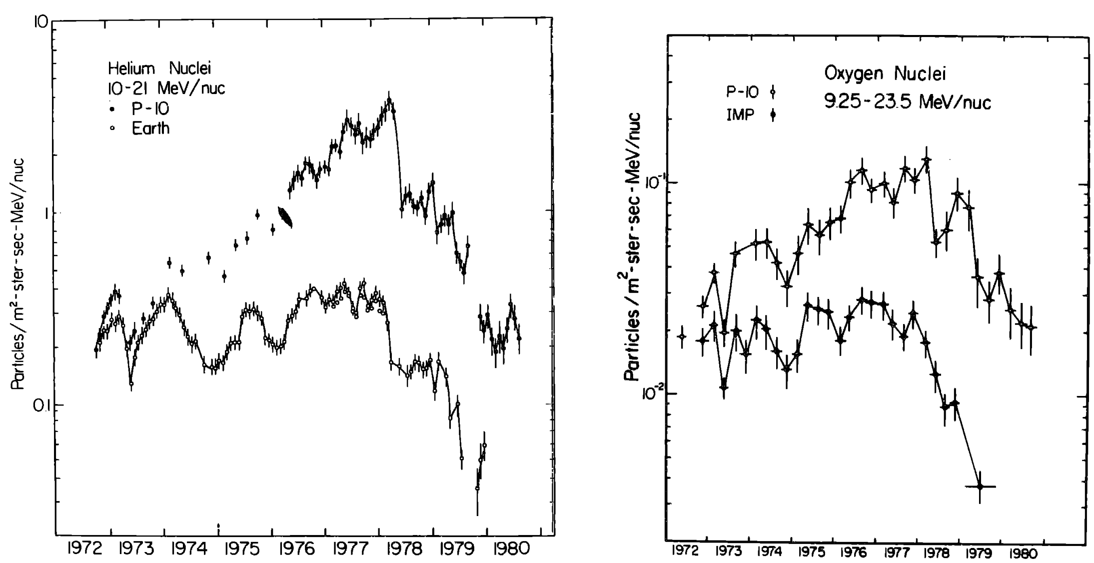

Figure 1a and b. Intensity of 10-21.6 MeV/nuc He nuclei and 9.5-23.5 MeV O nuclei at Pioneer 10 and at earth.

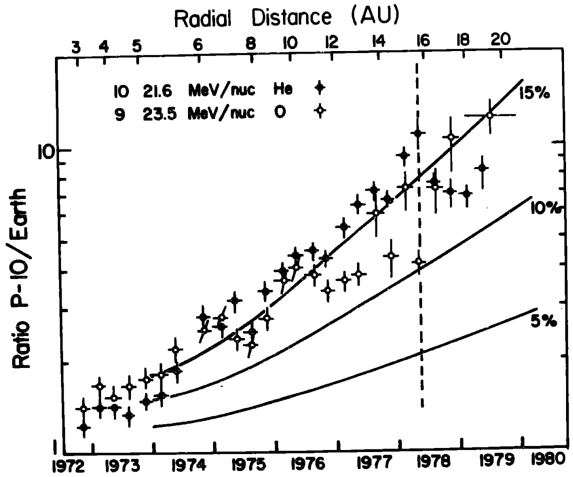

Fig. 2 Ratios of He & O intensities at P-10 and earth as a function of time. Dashed line indicates onset of large scale modulation effects.

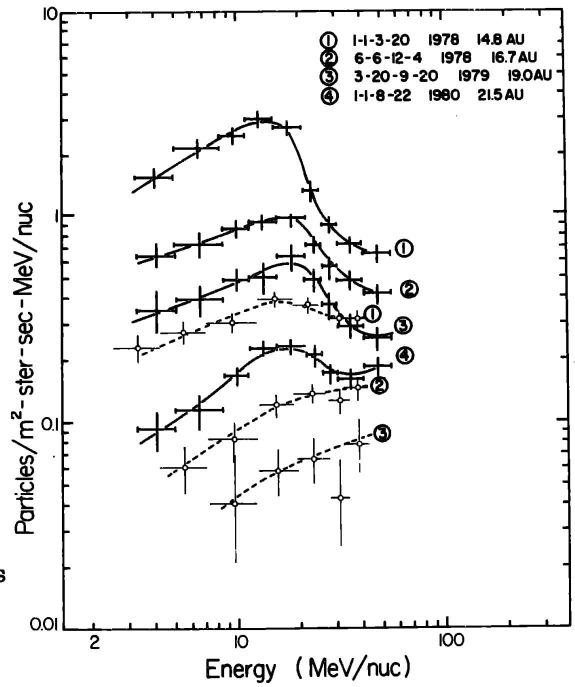

Figure 3. Differential intensities of He at P-10 ● and earth ○ .

3. Discussion of the Data.

A) The Radial Gradients. For both He and O the average radial gradient is 15 ± 3%/AU out to ∿ 15 AU. Beyond 15 AU, solar modulation effects greatly reduce the intensity of both components however the overall gradients are still ∿ 15%.

If the effects of particle streaming in the interplanetary medium can be neglected, then according to conventional modulation theory the gradient and the radial diffusion coefficient are related by $G_r = CV/K_r$. Both He and O have essentially the same velocity, and if they are fully ionized also the same rigidity and therefore the same K_r. The value of the Compton Getting coefficient C is somewhat larger for the O spectrum than for the He spectrum therefore for this situation O should have a larger gradient. This is not observed.

If these charges are singly ionized then O will have a much higher rigidity than He at the same velocity. This means that λ_r for O will be larger and since $K_r = 1/3\ v\lambda_r$, K_r will also be larger. This would suggest that O should have a smaller gradient than He, however, since C is somewhat larger for the O spectrum, this could balance the effects of K_r and lead to comparable gradients for the two species for this situation, as is observed. This will be explored quantitatively in a later paper.

B) Solar Modulation Effects. For the examination of the solar modulation effects it is useful to define the quantity m 3 $\ell n\ j_1/.j_2$ where j_1 and j_2 are the intensities at two different time periods. Using conventional modulation theory this can be rewritten $M = \Delta(CVR_B/K_r)$ e.g. the modulation is caused by a change in any or all of the parameters C, V, R_B or K_r. The changes in C may be directly determined from the ob-

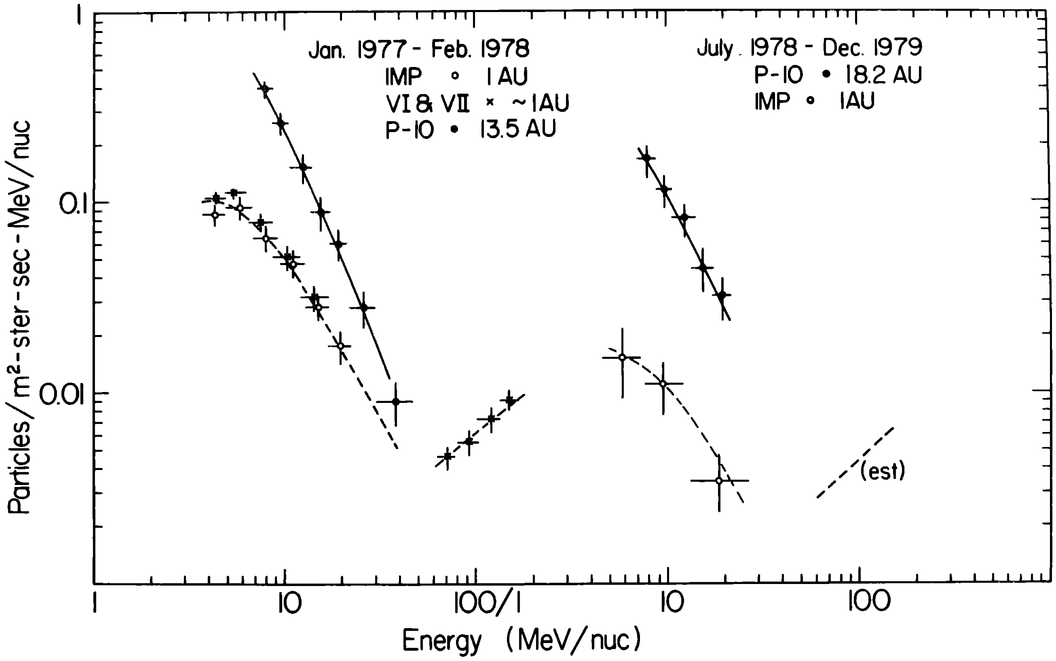

Fig. 4. Oxygen spectra at Pioneer 10 and earth for two time periods.

served spectral changes and these coupled with the known changes in V can only account for a factor ∿ 2 of the observed modulation which is a factor ∿ 10. To account for the overall modulation then requires large changes in either K_r or R_B.

Comparing now the relative modulation of He and O nuclei, assuming that changes in R_B are the same for both nuclei, we see that the situation is similar to that for the gradient except the relative changes in C/K_r now determine the relative modulation of these two components. From the data in Figure 3 and Figure 4 it is found that the He modulation is ∿ 1.4x the O modulation at the same energy/nucleon for the anomalous components at Pioneer 10. No abrupt changes in this modulation function as a function of energy are observed at the peak of either the anomalous He or O spectrum.

The expressions for the gradient and the modulation function may be combined to give $M/\Delta G_r \sim R_B$. The fact that almost no change in gradient is observed for a modulation of more than a factor of 10 sets a lower limit on R_B of several hundred AU. This behavior is very difficult to understand and along with some of the above observations may indicate the non-applicability of conventional modulation theory.

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